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Sequestration through forestry and agriculture

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Abstract

Current and future climate mitigation policies must resolve contentious issues regarding the inclusion of carbon sequestration created by changes in forestry and agricultural management practices in greenhouse gas emission reduction efforts. Terrestrial carbon sinks could be a low-cost mitigation option fosters conservation and development, yet issues related to verifying sequestration undermine confidence that emission offsets through sequestration are equivalent to emission reductions. From an atmospheric perspective CO_2 removals through sequestration are equivalent to emission reductions. But carbon will not remain sequestered in biomass or soils indefinitely and investments in sequestration could stifle investments in reducing emissions from other sources. Many climate agreements cap emissions from some countries (e.g., the Kyoto Protocol) or sectors (e.g., proposed climate legislation in the US) but enable participation of uncapped countries or sectors for forestry and agricultural sequestration. This structure can prompt emission increases in parts of the uncapped entities that weaken the value of emission reductions earned through sequestration. This has been a minor issue under the Clean Development Mechanism of the Kyoto Protocol. But Reduced Emissions through Deforestation and Degradation (REDD) is susceptible to the same problems related to sequestration established under current agreements. Success of REDD requires resolution of the challenges currently faced by forestry and agricultural carbon sequestration. The purpose of this article is to review the science, politics, and policy that form the basis of arguments for and against the inclusion forestry and agricultural sequestration as a component of current and future climate mitigation policies.

Introduction

Carbon lost from the world's ecosystems as trees have been cut down and soils have been disturbed has contributed about 90ppm of the observed increase in atmospheric CO_2 [1]. There is no question that much of the carbon that has been lost from ecosystems could be replaced given appropriate ecosystem management practices that enhance uptake of CO_2 or decrease release of CO_2, potentially sequestering substantial amounts of soil carbon in ecosystems. From an atmospheric perspective, activities that sequester carbon are equivalent to activities that reduce CO_2 emissions: both result in a net decrease in the growth rate of atmospheric CO_2 concentrations. This logic is embedded in the Clean Development Mechanism (CDM; Article 12) and Joint Implementation (JI; Article 4) sections of the Kyoto Protocol and the good-practice guidance for national inventories [2], which treat "net changes in greenhouse gas emissions by sources and removals by sinks resulting from direct human-induced land-use change and forestry activities, limited to afforestation, reforestation and deforestation since 1990," as fungible with reduction of greenhouse gas emissions. Policies making terrestrial sinks for atmospheric CO_2 equivalent to emission reductions have been adopted in other proposals [3], such as the US Climate Security Act of 2009. Public and private, voluntary and mandatory markets for such exchanges have evolved to apply this logic to projects that can contribute to national emission reductions. With a carbon price of 100 US$ per tCO_2, the agriculture [4] and forestry [5] sectors could sequester 12 Gt CO_2 yr^{-1} – compared with annual net emissions of nearly 30 Gt CO_2 yr^{-1} [6].

Despite the fact that CO_2 emissions and carbon sequestration are explicitly fungible in parts of the Kyoto Protocol, inclusion of carbon sinks has always been a contentious issue, influencing baseline emissions and emission targets and negotiating stances of different nations [7, 8]. Potential carbon sinks are unevenly distributed across the Annex I (developed) countries [9] with the distribution of potential sinks reflecting the imbalance of past emissions from land use change. Arguments from countries with large potential sinks to adopt a stance for broad inclusion of carbon sinks have been countered by arguments that sinks are qualitatively different from emission reductions [10]. A post-2012 agreement has been widely viewed as an opportunity to address the complexities and shortcomings related to sinks agreed to for the first Kyoto commitment period [11]. A key question lurking behind these discussions is: are forestry and agricultural carbon sequestration different enough than reducing carbon emissions that the two should not be fungible? Here I review the science, policy, and politics associated with efforts to sequester carbon via forestry and agriculture. I will briefly review the state of carbon cycle science, including practices that sequester carbon. This is followed by discussion of arguments in favor of pursuing carbon sequestration as a component of mitigation strategies. I then review the current status of international agreements and domestic polices focused on emission reductions, followed by discussion of arguments against carbon sequestration. Finally, I conclude by attempting to reconcile arguments for and against carbon sequestration.

Carbon cycling and carbon sequestration

All ecosystems – forested ecosystems, agroecosystems, grassland ecosystems, etc. – take up atmospheric CO_2 and mineral nutrients and transform them into organic products. Ecosystems are thus a major source and sink for the three main biogenic greenhouse gases – CO_2, N_2O, and CH_4. In undisturbed ecosystems, the carbon balance tends to be positive: carbon uptake through photosynthesis exceeds losses from respiration; even mature, old-growth forest ecosystems take up slightly more carbon than they release [12-14]. Disturbance, such as fire, drought, or disease, can lead to substantial losses of carbon from both soils and vegetation [15-17]. Disturbance is a defining element of all ecosystems that continues to influence the carbon uptake and losses that determine long-term ecosystem carbon balance [18].

Human land use activities often function much like natural disturbances in their influence on ecosystem carbon balance. Carbon dioxide is produced when forest biomass is burned, and soil carbon stocks begin to decline soon after disturbances to the soil (Figure 1)[19]. Like natural disturbances such as fire and drought, land use change affects vegetation and soil dynamics, often prompting longer-term increases in carbon release or decreases in carbon uptake.

Deforestation, degradation of native grazinglands, and conversion to cropland have prompted losses of 450-800 $GtCO_2$ from biomass and soil carbon pools – equivalent to 30-40% of cumulative fossil fuel emissions [20-23]. Emissions from deforestation have dominated carbon losses from terrestrial ecosystems [22], but substantial amounts of carbon have been lost from biomass and soils of systems other than forests as well [24].

Deforestation in tropical regions and decomposition of organic matter from drained peatland soils continues to contribute over 7 Gt CO yr^{-1}, or nearly 20% of total greenhouse gas emissions [5, 25]. On balance, though, the terrestrial biosphere is a net sink for carbon – taking up about 30% of total emissions [26]. The size of the terrestrial carbon sink is estimated as the difference between emissions and net atmospheric and oceanic uptake [27]. The location of the processes driving net uptake are varied and uncertain. Net carbon uptake by ecosystems is a common response to increased atmospheric CO_2 and nitrogen additions; but this accounts for just a small portion of the residual sink [28]. A major portion of the extratropical terrestrial carbon sink is probably attributable to forest regrowth driven by reversion of formerly agricultural land back to forest [29]. Thus substantial land area that was formerly disturbed by cultivation (soil disturbance), removal of carbon inputs (through harvest), and maintenance of highly productive but low biomass species (crops) has undergone a change in land use that is leading to net uptake of carbon by ecosystems – carbon sequestration – that is greater globally than emissions by deforestation.

Future carbon balance in forests and soils will be affected by a climate, though net global response of ecosystems remains uncertain due in part to several feedbacks [30]. Carbon stored in vegetation (~630 Pg C) and soil (at least 1600 Pg C, but perhaps as much as twice that [31]) is vulnerable to loss at warmer temperatures [32, 33]. Whether disturbances decline, mitigating future carbon losses, or the scope of human-induced disturbances continues to expand in the future is a very important determinant of future concentrations of atmospheric CO_2 [15, 34].

<u>Forestry sequestration potential</u>

After disturbance to forested systems, CO_2 fluxes from decomposition of exceed carbon fixation by photosynthesis, but this balance shifts over a period of a few years and regrowing forests begin to rebuild biomass and carbon stocks [13]. Options for sequestering carbon in forests are can be understood in terms of ecosystem recovery from disturbance: growing forests in land formerly forested (reforestation) or not (afforestation); lengthening the time between disturbances or enhancing productivity of forests (e.g., through forest management); and suppressing disturbance to keep forest carbon stocks intact (e.g., fire suppression). Similarly, reducing emissions from deforestation (RED) or from deforestation and degradation (REDD) is an effort to maintain carbon stocks by slowing or eliminating human-induced disturbance [35]. Reducing emission through deforestation and degradation is a reduction in emissions rather than carbon sequestration. But, many of the same benefits, detractions, and policy challenges apply. Other forest-related activities can reduce emissions (e.g., using renewable forest biomass resources to offset fossil fuel use) or enhance the life of wood products, but those are beyond the scope of this review.

The *technical potential* for carbon sequestration is very large – equivalent to all the carbon that has been released from soils [36]. The economic potential – the amount of carbon that would be sequestered given a specified price – is significantly less than what is technically possible. A high price for carbon ($US 75 t CO_2^{-1}) would lead to substantial amounts of carbon sequestered through forestation (400 Gt CO_2 between 2010 and 2100) whereas a lower price for carbon would lead to substantially less carbon sequestration (260 Gt CO_2 between 2010 and 2100 for $US 5 t CO_2^{-1}). The IPCC WGII Report on Forestry [5] synthesized data from several studies and estimated that by 2030 global afforestation could sequester between 1.6 and 2.4 Gt CO_2 yr^{-1} at carbon prices ranging from $US 25 to 100 t$CO_2^{-1}$. Altering forest management practices to increase carbon density within forest stands by maintaining partial forest cover, minimizing loss of dead organic matter, avoiding slash burning, planting immediately after harvest, fertilizing, or lengthening harvest rotation could sequester even more carbon: 1.8-5.9 Gt CO_2 yr^{-1} given prices ranging from $US 25-100 t CO_2^{-1} (Figure 2)[5]. The certainty of these values are characterized as "medium agreement, medium evidence," [5]. Estimates derived using global forest sector models enable comparison of sequestration potentials across nations, but they forecast substantially more carbon sequestration than regional (an average of 2.6x as large), bottom-up forest sector models, possibly because bottom-up assessments are able to account for institutional barriers [5]. Cost estimates vary widely for forest carbon sequestration projects [37], with average costs from peer-reviewed literature much higher than those in not-reviewed publications [38]. Intercomparison of sequestration cost studies is complex because of different assumptions about the competing desires of forestry managers to maintain economic profitability while changing practices to sequester carbon [39], incongruity of timing between investments, financial returns and risks [5], consideration of secondary benefits that arise with carbon sequestering activities, and leakage (implementation of forest activities that sequester carbon in one place but prompt releases in another)[37].

Carbon sequestration through improved forest management practices comprises a much larger proportion of total forestry carbon sequestration in temperate regions (55-63%) than tropical regions (18-27%)[40]. This corresponds with the distribution of forestry management plans capable of integrating carbon into consideration [41]. In developing countries, the largest portion (49%) of total carbon sequestration potential is associated with preventing deforestation, but deforestation is relatively unimportant in developed countries (4% of total potential sequestration)[5]. Nearly 80% of estimated potential carbon sequestration benefits in developing countries are accrued at carbon prices below $US 50 t CO_2^{-1} whereas in developed countries more than 40% of the carbon benefits accrue at carbon prices between $US 50 and 100 t CO_2^{-1} [5]. Uncertainties in afforestation, reforestation, and forest management impacts on forest soil carbon stocks are greater than those for biomass due to comparatively limited data [42]; increases or decreases may be expected in different regions or for different types of forest [43]. Soil carbon stocks tend to increase when land is converted from cropland to forest, but decline when converted from native forest to plantation or pastures [44]. Forest management practices that enhance production or suppress disturbances tend to build soil carbon stocks [45].

Unless policies are implemented to slow the rate of deforestation, a decade's worth of fossil fuel emissions could released by forest clearing through 2100 [35]. As these emissions arise primarily from developing countries, the Kyoto Protocol does not constrain deforestation emissions; the CDM and JI also do not address deforestation as a mitigation strategy. In preparation for a post-2012 climate regime, the United Nations Framework Convention on Climate Change is investigating scientific, technical, and policy issues affecting the feasibility of

REDD [35]. Like forest sequestration, the contribution from reducing deforestation to lowering total emissions could be a substantial – between 2000 and 2005, gross deforestation was 12.9 Mha yr^{-1} while global forest area declined by a net of 7.3 Mha annually (Figure 2)[5]. The IPCC synthesis estimates that 2-4 Gt CO_2 yr^{-1} would be retained in ecosystems given prices ranging from $US 25-100 t CO_2^{-1} [5]. The bulk of this potential is in Central and South America (46%) and Africa (29%) – places where deforestation is most important. Based on estimated biomass carbon stocks [5] and deforestation rates between 2000-2005 [46], maintaining these ecosystem carbon stocks would require preservation of 11-22 MHa in Central and S. America and 8-16 MHa in Africa compared with deforestation rates of 20 and 24 Mha yr^{-1} [46] and 104 and 57 Mha currently designated for conservation in Central/S. American and Africa, respectively [47].

<u>Agricultural sequestration potential</u>

Disturbance is an integral part of traditional agricultural management systems that fosters dependable yields of a single crop for food, fuel or fiber by controlling weeds, preparing a uniform seed bed, and ensuring sufficient nutrient and water supplies. But disturbances also deplete agricultural systems of carbon stocks [48]. Tillage is used to enhance seed beds and controls weeds, but tillage also breaks up soil aggregates, changes soil microclimate, and enhances decomposition of soil organic matter and depletion of soil carbon stocks [49]. Bare fallow enhances the water balance, but substantially reduces carbon inputs [50]. Harvesting a large proportion of plant biomass enhances yields of useful material, but decreases carbon inputs to the soil [51]. Like carbon sequestration in forests, sequestration in agricultural systems – primarily, but not entirely in the soils – is brought about by decreasing disturbances. Reversing disturbance and sustaining aboveground biomass, high productivity, low harvest index, short bare fallow periods (or elimination of fallow), cover crops, and large root biomass all promote increased carbon. Of course the agricultural management practices that disturb the system and prompt carbon losses are intended to boost production, but the complement is not necessarily true: practices that sequester carbon do not necessarily result in reduced yields. Practices that sequester carbon can often enhance producer income.

Tillage has been used ubiquitously in agriculture to prepare the seed bed, to incorporate fertilizer, manure and residues into the soil, to relieve compaction, and to control weeds [52, 53]. But tilling the soil is disruptive and can promote soil erosion, high soil moisture loss rates, degradation of soil structure and depletion of soil nutrients and C stocks. Following long-term tillage soil C stocks can be reduced by as much as 20-50% [54-57](Figure 1). Conservation tillage (reduced soil stirring, reduced area affected, or reduced frequency) and no-tillage are common has been spreading globally [58]. Conservation and no-tillage decrease the negative impacts of tillage, preserves soil resources, and can lead to accrual of much of the soil carbon lost during tillage [49, 59, 60]. Data from West and Post [61] show that on average, a change from conventional tillage to no-till can sequester 0.6 t C ha^{-1} yr^{-1}, though results vary as a function of soil type, climate, and land use history. The accumulation of carbon will continue (provided the soil is not tilled) and soil carbon sequestration rates peak after 5 to 10 yr, with soil carbon reaching a new equilibrium after 15 to 20 yr [61]. Some of the carbon that has been sequestered is lost upon tillage, but land under periodic tillage to control weeds or soil compaction still retains more carbon than conventionally-tilled soils [62]. Conservation and no-tillage also reduce energy use and minimizes CO_2 losses from decomposition in drained histosols [63].

Cover cropping, green manuring, catch crops, and more complex crop rotations all increase carbon inputs to the soil by extending the time over which plants are fixing atmospheric CO_2. Green manures and catch crops have the benefit that they enhance system nitrogen balance, which further increases productivity. Growing cover crops enhances soil protection and groundwater quality, controls pests, and increases carbon stocks by enhancing carbon inputs when ground would otherwise lay fallow [64, 65]. Using green manures can simultaneously build soil carbon and nitrogen stocks [66-68], enhancing soil fertility and sequestering carbon in the soil, but likely increasing N_2O emissions. Use of catch crops also tends to sequester carbon in the soil [69-71]. A more complex rotation involving multiple crops over one or more years enhances soil carbon stocks by an average of between 0.07 t C ha^{-1} yr^{-1} and 0.24 t C ha^{-1} yr^{-1} [4, 61]. Rotations with grass, hay, or pasture tend to have the largest impact on soil carbon stocks [61]. Reduced carbon inputs associated with more frequent bare summer fallow in semi-arid regions reduces the level of soil organic matter in dryland agricultural systems [72]. Reducing the frequency of bare fallow leads to carbon sequestration by increasing the time over which carbon is taken up by plants in input to the soil [66]. In semiarid regions alternate-year fallow is used to collect soil moisture; conservation tillage is often required to enable reduction of fallow frequency [73]. Conservation tillage coupled with reduced fallow frequencies have been used successfully in a variety of semiarid environments to sequester carbon in soils [64, 66, 73, 74]. If production and carbon inputs decrease with decreasing fallow frequency, soil carbon stocks can decrease [75].

Grazingland management to enhance production (through sowing improved species, irrigation or fertilization), minimize negative impacts of grazing, or rehabilitate degrade lands [76-78]. Improved grazing management (management that increases production), leads to an increase of soil carbon stocks by an average of 0.35 t C ha^{-1} yr^{-1} [77]. Agroforestry enhances carbon uptake by lengthening the growing season, expanding the niches from which water and soil nutrients are drawn, and in the case of nitrogen-fixing species, enhancing soil fertility [79]. The result is that when agroforestry systems are introduced in suitable locations, carbon is sequestered in the tree biomass and tends to be sequestered in the soil as well [80]. Improved management in existing agroforestry systems could sequester 0.012 Tg C yr^{-1} while conversion of 630 Mha of unproductive or degraded croplands and grasslands to agroforestry could sequester as much as 0.59 Tg C yr^{-1} by 2040 [81], which would be accompanied by modest increases in N_2O emissions as more nitrogen is fixed.

Adding manure to soil builds soil organic matter in croplands [4] and in grasslands [77]. The synthesis by Smith et al. [48] suggests that adding manure or biosolids to soil could sequester between 0.42 and 0.76 t C ha^{-1} yr^{-1} depending on region (sequestration rates tend to be greater in moist regions than in dry). Rapid incorporation of manure into fields would reduce the time that manure decomposes in anaerobic piles and lagoons, reducing emissions of CH_4 and N_2O. Smith et al. [4] estimate the technical potential for reduction of CH_4 emissions from manure to be 12.3 Tg C yr^{-1} by 2030; N_2O emissions could also be reduced. Adding manure in one place to build soil carbon stocks is offset by removal or what would be carbon inputs in another place (by forage or feed harvest); the balance between these has not been well characterized.

Globally an estimated 1.1-2.5 Gt CO_2 yr^{-1} could be sequestered in agricultural soils given carbon prices of $US 20-100 t CO_2 (Figure 2). Most of the potential sequestration is through changes in management practices in existing cropland, particularly when carbon prices are lower (16% at $25 t CO_2^{-1} versus 7% at $100 t CO_2^{-1}). Despite lower per area carbon sequestration rates, improved management of grazinglands is estimated to be capable of sequestering 0.2-0.7 Gt CO_2 yr^{-1} worldwide because grazinglands cover such a large portion of the Earth's surface (about one-quarter of the terrestrial surface, compared with about 10% for cropland)[46, 82]. Nearly 2000 Mha of land worldwide have been degraded to some degree by mismanagement [83]. Much of this land can be rehabilitated by enhancing plant productivity, capturing water resources and using them more efficiently, or improving soil fertility; doing so could sequester about as much carbon as could be sequestered in grazinglands (0.15-0.7 Gt CO_2 yr^{-1} depending on carbon prices)[4].

Arguments *for* forestry and agricultural sequestration

One of the main arguments for forestry and agricultural sequestration is that the impending climate impacts are real and potentially severe, so all options to reduce greenhouse gas emissions should be pursued. The principle of comparative advantage suggests that a wider range of options should generate lower costs initially and overall. The potential contribution of forestry and agricultural sequestration to mitigate greenhouse gas emissions is large – together rivaling the potential emission reductions from the energy supply, transportation, buildings, waste, and industrial sectors at low prices for carbon ($20 tCO_2) and exceeding all sectors at high carbon prices ($100 tCO_2)[6]. The IPCC [6] estimated that forestry and agriculture would sequester approximately 8 Gt CO_2 yr^{-1} given carbon prices of $100 tCO_2; including reduced emissions from deforestation and degradation would maintain an additional 4 Gt CO_2 yr^{-1} in the soil, raising total contribution of the land sectors to about one-third of total annual global emissions (i.e., 12 Gt CO_2 yr^{-1} out of 30 Gt CO_2 yr^{-1})[6]. Substantial amounts of CO_2 emission from the land sector and large potential for sequestration with changes in land management are amongst the most important points in arguments in favor of forestry and agricultural sequestration offsets.

A second argument in favor of forestry and agricultural sequestration is that implementation of practices to sequester carbon can lead to increased production and greater economic returns. A variety of land management practices lead to near-term increases in both production and sequestration of carbon. For example, reduction of bare fallow frequency in croplands increases carbon inputs, makes more efficient use of limited rainfall, and increases crop yields [50]. Introduction of conservation tillage reduces tractor and fuel usage and costs, making the marginal cost of abatement through conservation tillage negative [84]. Programs to rebuild soil organic matter stocks through rehabilitation of degraded lands will restore productive capacity [85]. When soil carbon stocks are built by suppressing biological processes that lead to carbon outputs, other aspects of decomposition will be slowed too – like turnover of mineral nitrogen. In such cases, the production benefits attributable to enhancing carbon stocks may not be apparent while organic matter stocks are building, but may be later [86]. Adding manure or mulch to soil in order to build soil carbon stocks requires inputs of materials that are often used for other purposes (e.g., household energy production), thus production and economic benefits will not accrue immediately, but could over the longer-term.

Some practices that sequester carbon require land managers to forgo optimal harvest (e.g., lengthening forest harvest cycles), tolerate reduced yields (e.g., reduced stocking rates), or change land use (e.g., cessation of cultivation of organic soils); others require investments in new equipment that could be substantial (e.g., no-till drills for planting). But the primary investments necessary for successful widespread adoption of many of the land management practices that enhance ecosystem carbon storage are knowledge, education, and information. Most of the materials required for implementation of many practices that sequester carbon (e.g., improved crop rotations, cover crops, agroforestry, shelterbelts, reduced bare fallow frequency, integrated pest management, longer forest rotations, mulching, improved grazing, and livestock management, less disruptive forest harvest) are not different than those required for conventional land management practices – they differ primarily in their implementation. Thus technical requirements are modest and marginal abatement costs are estimated to be negative in some cases (such as adoption of no-tillage in the US and UK)[84, 87].

Carbon emissions from land use change arise primarily from developing countries – countries which are exempt from emission reductions under the Kyoto Protocol. Widespread disturbance and degradation [88] and continuing deforestation make carbon sequestration and preservation (i.e., REDD) substantial sequestration opportunities in developing countries [9, 78, 89]. Engagement of developing countries in emission reduction activities is another argument in favor of forestry and agricultural carbon sequestration [8]. Given modest costs and use of existing technologies, carbon sequestration in developing countries could be enacted in the near-term, offsetting emissions from other sectors now, allowing time for the larger investments required to directly reduce emissions from burning fossil fuels [90]. Investments in carbon sequestering practices in developing countries that increase agronomic or forestry efficiency or productivity are likely to promote relatively immediate sustainable agriculture and forestry returns. The economic, environmental, and social costs of land degradation are substantial [91] and investments in sustainable land management tend to be an efficient use of limited development resources [92]. New knowledge about best practices is likely to be required in order to have a meaningful impact in much of the developing world.

Many land management practices that sequester carbon prompt other changes in environmental processes that are also beneficial. Several practices with the largest potential to sequester carbon were developed to address issues other than carbon sequestration. For example, reduced- and no-tillage derived from efforts to control wind and water erosion [93]; forest preservation practices have been implemented to ensure water quality and sufficient water supply [94]. Agricultural and forestry practices that promote greater vegetative (buffer strips, grassland conservation, reduced bare fallow, etc.) or litter (reduced tillage, reduced harvest index, selective harvest, etc.) cover reduce wind- and water-driven soil erosion. Practices that preserve habitat, like forest preservation, reforestation, agroforestry, etc., can preserve species and biodiversity. Even in uncut areas surrounding areas of deforestation, the supply of ecosystem services tends to decline after deforestation [95]. A variety of practices that sequester carbon (catch crops, cover crops, crop rotations, etc.) also retain nutrients in agricultural systems, reducing downstream pollution [96]. Carbon sequestering practices can also enhance ecosystem water balance; building soil organic matter stocks tends to enhance water infiltration and soil moisture status in arid/semiarid environments [e.g., 97].

Mitigation investments are important for reducing greenhouse gas concentrations, but greenhouse gas concentrations will continue to increase for decades despite implementation of even the most aggressive climate policies [25]. Adaptation to changing climates is inevitable [25]. Many of the practices that sequester carbon enhance resilience to climate variability and could foster adaptation to future climate [5]. Synergy between practices that mitigate climate changes while simultaneously fostering adaptation to climate change are another argument in favor of forestry agricultural carbon sequestration. No-tillage management, for example, increases residue cover and decreases evaporative losses from the soil profile, thus enhancing moisture availability, reducing plant water stress, and increasing yield [98]. Climate change may make forests more vulnerable to carbon losses driven by disturbance (pests and fire)[99-101], forest management practices that produce uneven-aged stands could reduce the likelihood of those disturbances [102, 103].

Carbon sequestration in emission reduction policies

The overall goal of the Kyoto Protocol is the "stabilization and reconstruction of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system*." The principle of "common but differentiated responsibilities" in the Kyoto Protocol regulates emissions on Annex I countries, but encourages developing country participation through the CDM. The current rules for the land use, land use change, and forestry projects under the CDM, adopted at the Seventh Conference of the Parties (COP7) in 2001 resulted in an agreement that permits afforestation and reforestation carbon offset projects in developing countries, but with complex monitoring and reporting requirements and exclusion of deforestation emissions [10]. Emissions from afforestation, reforestation, and deforestation since 1990 are reported as part of United Nations Framework Convention on Climate Change (UNFCCC) official National Communications that will determine compliance with Kyoto Protocol emission reduction targets. The CDM is designed to lower costs for achieving that goal while encouraging participation of non-Annex I countries and helping foster sustainable development [104]. The CDM has always been a contentious issue [105]; countries with large sinks tended to favor including terrestrial carbon sinks in negotiations while countries with small sink potentials tended to oppose inclusion [8]. Many developing countries strongly supported inclusion of sinks in anticipation that emission caps would substantially increase the flow of aid – in the form of emission offset projects – from developed countries [106]. Science (and scientists) played a key role in determining whether and how forest and agricultural sinks should be included in the Kyoto protocol, ostensibly acting as a boundary organization linking science and policy [107, 108]. Review of relevant published studies suggests that natural scientists have tended to favor inclusion of sinks more than economists and social scientists [109]. This may have contributed to adoption of definitions of climate change [110] and "direct, human-induced" sinks that have led to confusion and accounting challenges [111]. Stances based on anticipated development assistance benefits have flavored discussions on rules governing REDD [112] and related demands for a "Marshall

* Kyoto Protocol, Article 2.

Plan" for adaptation assistance*. The compromise of partial sink inclusion reached through the CDM is clearly an important item for discussion for post-2012 climate agreements [11].

Inclusion of sinks through the CDM allows participation of a wide range of actors in emission reduction efforts, but puts strict limits on only a subset of those participants. The US Clean Energy and Security Act of 2009† is similar to the Kyoto Protocol in that it caps some sectors, but allows for carbon sequestration from agricultural and forest carbon sinks. Both policies are designed to enable entities facing emission caps to invest in lower-cost emission reduction options. The CDM is closely integrated with the European Emissions Trading Scheme that was designed to help EU countries meet Kyoto emission caps; capped industries are purchasing offsets to meet a substantial portion of mandated emission reductions [113]. The use of offsets – emission reductions or sequestration from an upcapped sector or activity – to meet emission reduction requirements of another sector is designed to enable flexibility in meeting emission caps [10]. It also incentivizes capped entities to outsource emission reductions. Excluding sectors or nations from emission caps and enabling their participation via offsets could also incentivize outsourcing of emissions – growth in exports account for half of China's emission growth even with limited worldwide success in meeting Kyoto Protocol emission targets [114].

Under the Marrakesh Accords, projects that reduce greenhouse gas emissions "below those that would have occurred in the absence of the registered CDM project activity'' are eligible for credit under the CDM [115].The key challenge for projects from uncapped sectors or countries – for all types of offset projects, not just sequestration projects [3] – is proving the counter-factual: convincingly demonstrating what would have been done in the absence of carbon sequestration incentives (additionality – is the practice *additional* to what would have been done?) and how implementing a new practices has affected the behavior of other actors (leakage – are afforestation projects driving deforestation?). Methods of assessment have been developed [116] and various rules have been proposed [e.g., 117] and applied [see 104, 109] to address additionality and leakage. To-date results of carbon emission offsets under the Kyoto Protocol have been mixed [104]; several projects of dubious emission reduction value have been approved [118] and few sequestration projects have been accepted. Research addressing the feasibility of the CDM continues to address this issue [104].

Carbon sequestered in forest biomass or in soils is subject to reversals – carbon emissions caused by disturbance [119]. Such disturbances can be large or small, intentional or unintentional [e.g. 15]. The CDM has dealt with this issue by developing temporary Certified Emission Reductions (CERs) for five or twenty year periods [105] while other standards reduce emission reduction credits to buffer against losses ‡. Impermanence decreases the value of sequestration projects compared with emission reduction projects and increase uncertainty and transaction costs [120]. Resolution of additionality, leakage, and permanence issues are critical for acceptance of REDD in a post-2012 climate agreement, as is identification of a pre-agreement baseline against which deforestation/degradation reductions can be evaluated [112].

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* "Poor nations need 'wartime' support against climate change: UN". AFP. 1 September 2009.

† US House Act HR2454: American Clean Energy and Security Act of 2009

‡ e.g., The Voluntary Carbon Standard (http://www.v-c-s.org/)

Policies other than climate policies have a large influence over the management of agricultural and forested land and a corresponding influence over carbon stocks and fluxes [121]. National polices devoted to land conservation, set-asides, and crop rotations to conserve highly erodible land (e.g., the Conservation Reserve Program in the United States and Ecosur promotion of no-tillage), national or regional macroeconomic policies, regional agreements on agricultural policy (e.g., the EU Common Agricultural Policy), and International agreements like the UN Conventions on Biodiversity and Desertification all prompt changes in land use that can lead to carbon sequestration (or release). Policies promoting biofuel production, either to reduce greenhouse gas emissions or increase energy security, will continue to have an impact nationally and internationally [122-124].

Arguments *against* forestry and agricultural offsets

One of the primary arguments against forestry and agricultural offsets is that they would delay implementation of the more fundamental shifts in emission reduction and decarbonization. The limited number of forestry projects under the CDM suggest that this concern has not been realized, but concerns about additionality in non-forestry CDM projects [118] suggests that such concerns are legitimate. Alternatively, the small number of projects to-date may indicate that the role of forestry and agricultural carbon sequestration may be small despite large potential for sequestration and large land use-related emissions.

Demonstrating additionality is a formidable challenge [125-127], requiring information other than sampling of biomass or soil carbon stocks [128]. Policies that incentivize adoption of behavioral (i.e., land management) changes are confronted by additionality and the potential for perverse incentives – which in the case of forestry and agricultural sequestration could encourage land owners to get rid of ecosystem carbon through tillage, fire, or harvest so that they could then be paid to re-sequester it. All policies, grants, or investments that fund or incentivize some action implicitly assume that the action would not have taken place in the absence of policy implementation. Public funds comprise much of the CDM transactions to-date [90]. Additionality issues may be scrutinized more closely as private participation grows. The challenge of additionality exists in all types of offsets [3], but the difficulty is compounded in forestry and agricultural carbon sequestration projects because the direct, human-induced changes in carbon stocks must be distinguished from changes in carbon stocks driven by natural processes (e.g., biomass carbon stock recovery after a fire) and indirectly by human actions (e.g., enhanced biomass carbon stocks driven by CO_2 fertilization or nitrogen deposition; increased soil carbon stocks driven by shifts in species composition)[111]. In theory such changes could be documented by sampling, but disentangling drivers of carbon stock changes remains challenging [129-131].

The anticipated low costs of forestry and agricultural carbon seqeustration are intimately intertwined with the additionality issue – if barriers (i.e., costs) are low for adopting practices that sequester carbon, they are more likely to be adopted in the absence of policies to promote them. Despite management practices that can be introduced using existing technologies, some work suggests that land owners may wait for carbon prices to rise substantially before adopting new, sequestering practices, raising the costs to initiate action to $275-375 per t CO_2 [40]. This also suggests a delay between policy implementation and action, possibly resulting in little C sequestered in forests over next 20 years, making forest sequestration inappropriate as a stopgap measure [40]. Further, high carbon prices are likely to prompt substitution for wood products [132], potentially reducing effectiveness. Documenting changes in biomass or soil carbon stocks will require some kind of measurement coupled with extrapolation or interpolation [128]. These measurements differ from those required for other types of offset projects, they contribute more significantly to project costs, and economies of scale may not be as effective at reducing costs. Enacting a project in which several land owners enact carbon sequestering practices would require documenting the effect of those practices (collectively or individually) on each parcel. These difficulties lie not in measuring carbon stocks, but in devising measurement/monitoring/verification systems that are accurate yet cost-effective [128].

Because a key argument in favor of forestry and agricultural carbon sequestration through the CDM – and of CDM offsets in general – are the perceived development benefits, the lack of development benefits to-date suggests that mechanisms like the CDM should not be policy priorities. Investments via the CDM generally seek the lowest-cost CO_2 emissions offsets, not necessarily prioritizing for development [90], producing limited investment in new infrastructure and resulting in little development success [133, 134]. Small-holder households represent a serious challenge for documenting carbon sequestration [135] because aggregation across a variety of landowners increases monitoring transaction costs, implying that the cost-effectiveness of carbon sequestration projects conflicts with poverty alleviation goals [136, 137]. In many of the places identified as having low-cost sequestration options, a large percentage of people make their living from the land; compensation for changing practices could be financially beneficial, but may be of limited development value. Uncertainty about land-tenure amongst small-holders and weak institutions are key issues that discourage potential participants from adopting carbon sequestering practices [138]. Practices that sequester carbon are not inherently coupled with other environmental benefits either. Nelson et al. [139] found that in the Northwestern US sequestration policies did not necessarily achieve forest conservation goals and none of the conservation policies studied sequestered carbon. Similarly, the CDM has not yet led to forestry mitigation that successfully foster adaptation to climate change [103].

The final argument against forestry and agricultural carbon sinks is that scientific information lags behind the desire to craft robust policies: there are too many uncertainties to proceed. For example, conservation tillage is one of the largest potential sources of greenhouse mitigation within the agricultural sector [48] and, coupled with associated declines in fuel use, could make an immediate, substantial contribution to offsetting and reducing greenhouse gas emissions [140, 141]. However, implementation of reduced- or no-tillage does not always lead to significant increases in carbon stocks [142, 143]. In some cases depletion of soil carbon stocks at depth offset gains in surface soils; the mechanism driving this process is not well-understood [144, 145]. There is also uncertainty about how practices that sequester carbon impact local climate through albedo and water balance [146]; practices that lead to reduced greenhouse gas concentrations could promote local warming [147]. Practices that sequester carbon could also lead to increased N_2O (e.g., fertilization to enhance carbon inputs; adoption of no-tillage) or CH_4 (e.g., flooding to preserve organic soils)[148, 149]. The contribution to erosion to depletion of soil carbon stocks, and the fate of eroded carbon are additional important uncertainties [150]. Finally, disturbances are stochastic and often unpreventable processes that can lead to carbon losses [131] and ecosystem and socio-economic feedbacks (i.e., leakage, unintended consequences) are capable of undermining the intended benefits of forestry and agricultural sequestration projects [137].

Reconciling arguments for and against forestry and agricultural carbon sequestration

The arguments against fungibility of forestry and agricultural sequestration with emission reductions can be grouped into three categories: those that deny the claims of cost-effectiveness and claims of development, environmental, or engagement co-benefits of sequestration; those that question the feasibility of documenting carbon offsets generated by sequestration; and those that suggest sequestration would impinge on other emission reduction efforts or investments. Arguments that question (or promote) alternative benefits for a particular class of emission reductions (or sequestration) are immaterial for resolving the fungibility question. Formal analyses of the impacts of sequestration on other emission reduction efforts are lacking. Scant data from CDM projects could be interpreted to mean that international projects are a low priority or that the documentation procedures for projects are to rigorous. On the other hand, data from national communications on greenhouse gas emissions submitted to the United Nations Framework Convention on Climate Change are numerous and reported according to rigorous national level documentation requirements. Data from the most recent reports show that there is no relationship between the size of land use change and forestry (afforestation, reforestation, and deforestation since 1990; LUCF) and emission growth rates[*]. However, emission growth rates between 1990 are positively correlated (Figure 3; r^2=0.17; P=0.007) with LUCF-sector growth rates – countries that most successfully reduced non-LUCF emission between 1990 and 2006 had decreases or small increases in sequestration whereas countries with the highest emission growth rates tended to have the largest growth in LUCF carbon sequestration. Causation is not clear, thus these data could indicate that investments in LUCF sequestration have had a negative impact on emission reduction efforts or that investments in LUCF have paid immediate dividends in terms of sequestration. Time will tell.

Kyoto and subsequent negotiations have resulted in a complicated set of rules for evaluating carbon sequestration for a limited set of practices. This “constructive ambiguity” and subsequent refinement of rules [7] has likely led to difficulty implementing carbon sequestration projects under the CDM. However, the methods used for National Inventories for UNFCCC reporting for the LUCF-sector have evolved from standardized, uniform Tier 1 approaches with set emission reduction factors to a variety of accepted approaches. A key to the success of future negotiations is the development of flexible standards that tackle the additionality issue which can be applied to projects. If such agreements are reached, the variety of forestry and agricultural practices that can contribute to sequestration will be expanded, possibly including the 30% of emission arising from deforestation and degradation and possible engaging developing country participation in a post-2012 climate regime.

[*] All data used for this analysis are taken from the most recent UNFCC National Communications (available at http://unfccc.int).

Figure captions

Figure 1. Undisturbed ecosystems tend toward equilibrium with respect to biomass and soil carbon stocks. Upon natural (e.g., fire, drought, etc.) or human-induced (e.g., deforestation, tillage, etc.) disturbance, carbon stocks tend to decline. Carbon stocks can be re-built by adopting land management practices that eliminate, reduce, or delay disturbance. (After [19]).

Figure 2. Emissions and LUCF-sector sequestration from 1994 for Annex I and non-Annex I countries* contrasted with carbon sequestration potential in 2030 through agricultural [4] and forestry practices [5] and reduced emissions from deforestation and degradation (REDD) [5].

Figure 3. Annual emission growth rates (percent per year) as a function of (A) LUCF-sector emissions as a percentage of total non-LUCF emissions and (B) annual LUCF-sector growth rates. Positive numbers for LUCF-sector emissions as a percentage of total emissions (A) indicate net carbon loss from LUCF.

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*All emissions and LUCF data are from UNFCCC compilations of National Communications.

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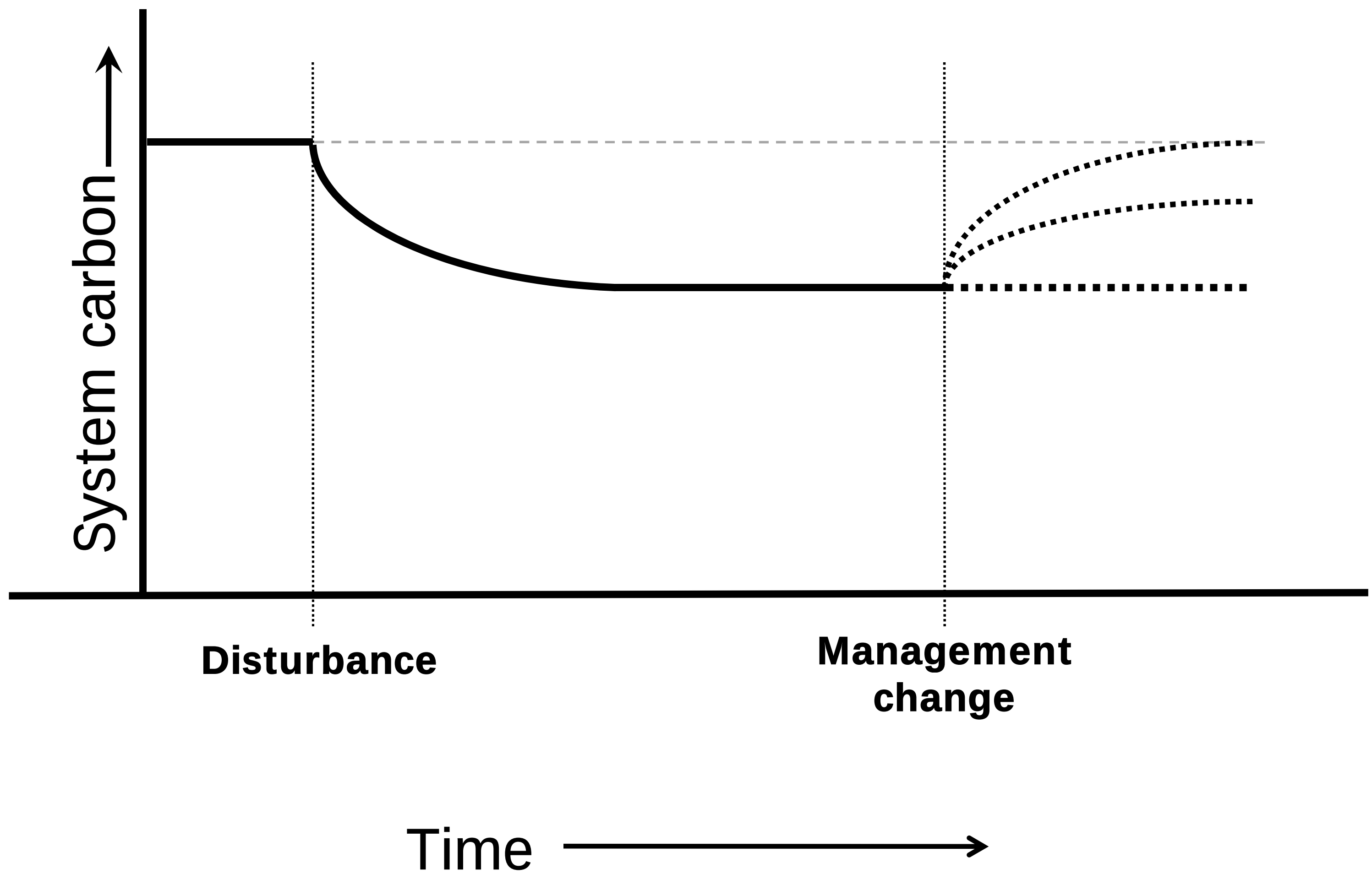
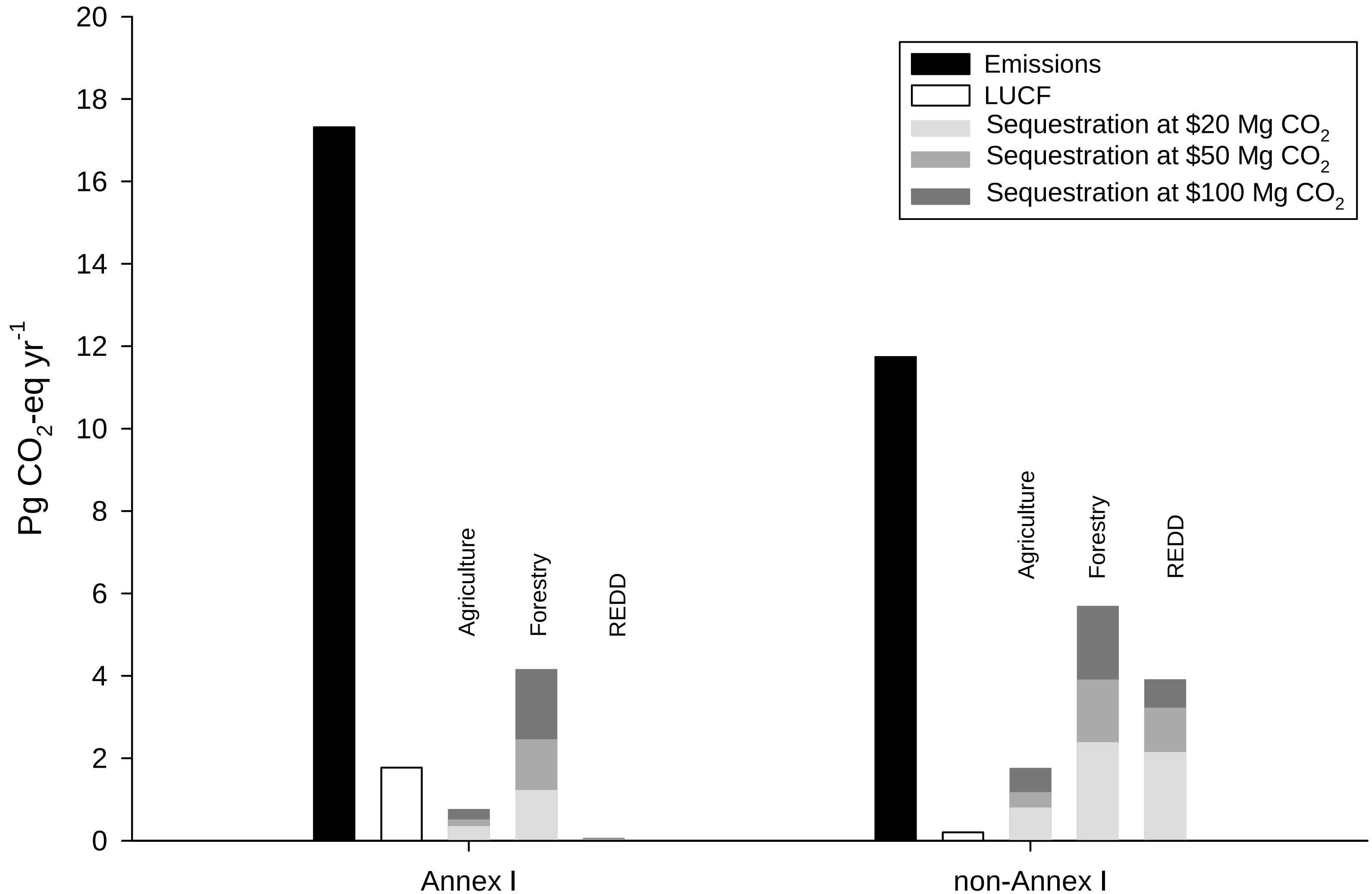


Figure 1



20
18
16
14
12
10
8
6
4
2
0
Pg CO2-eq yr-1
Emissions
LUCF
Sequestration at $20 Mg CO2
Sequestration at $50 Mg CO2
Sequestration at $100 Mg CO2
Agriculture
Forestry
REDD
Agriculture
Forestry
REDD
Annex I
non-Annex I

Figure 2

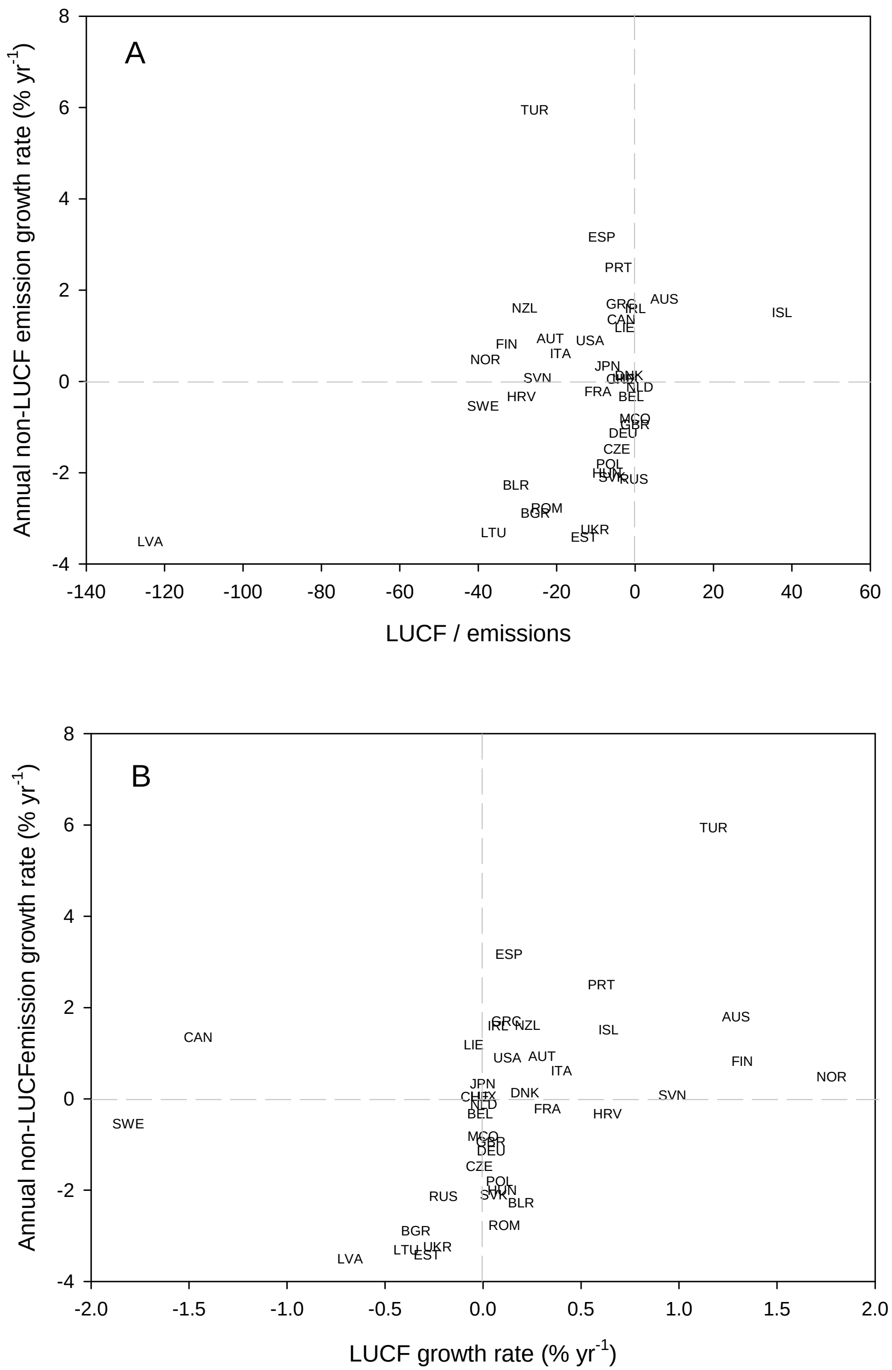

A
Annual non-LUCF emission growth rate (% yr-1)
LUCF / emissions
TUR
ESP
PRT
GRC
IRL
AUS
ISL
NZL
CAN
LIE
FIN
AUT
USA
ITA
NOR
JPN
DNK
SVN
NLD
FRA
BEL
HRV
SWE
MCO
GBR
DEU
CZE
POL
RUS
BLR
ROM
BGR
LTU
UKR
EST
LVA
B
Annual non-LUCFemission growth rate (% yr-1)
LUCF growth rate (% yr-1)
CAN
SWE
FIN
NOR
SVN
HRV

Figure 3